

# Recent Stratigraphy and Pollen Analysis of Lomawai and Kubulau Mangrove Areas, Fiji

Joanna Ellison<sup>1</sup> and Pippa Strickland

School of Geography and Environmental Studies,  
University of Tasmania,  
Private Bag 78, Hobart 7001, Australia.

<sup>1</sup>Corresponding author. Email: [Joanna.Ellison@utas.edu.au](mailto:Joanna.Ellison@utas.edu.au)

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## Abstract

Late Holocene sea level trends of two significant mangrove areas in Fiji were reconstructed by transect-sampled stratigraphic cores, at Lomawai on the western coast of Viti Levu, and Kubulau on the southern coast of Vanua Levu. These cores were investigated using percent organic, radiocarbon dating, and pollen analysis techniques to reconstruct environmental history of the Late Holocene. Results showed at Lomawai that mangroves occurred to at least 3 meters below present, and with a micro-tidal range of mangroves of 1 meter or less this indicates relative sea-level rise at the site in the last 1,000 years at least, consistent with regional subsidence. At Kubulau, stratigraphy was relatively shallow, with little evidence of mangrove presence below current levels suggesting tectonic stability. Inorganic sedimentation at both sites indicated high levels of allochthonous sediment input in association with catchment delivery, with sedimentary rates of around 1.1-2.0 mm a<sup>-1</sup> under the present mangroves, though more rapid at the Lomawai seaward edge, perhaps in association with disturbance. The Lomawai mangrove area has been keeping up with relative sea level rise rates higher than global rates in the last several hundred years, with replicated evidence of mangrove stratigraphy far lower than present tidal levels. While mangroves have kept up, there has been a slow landward migration of mangrove zones over the centuries indicating that the rate or relative sea level rise has been slightly higher than the sedimentation rates. Hence both Lomawai and Kubulau mangroves are vulnerable to global increases in the rate of sea level rise, which can be mitigated by continued catchment sediment delivery, and other actions to retain mangrove resilience.

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## 1.0 Introduction

There has been limited development of methodologies for vulnerability assessments and adaptation strategies that are specifically useful in mangroves, or even in associated systems. Rather, most climate change vulnerability assessments have focused on particular human sectors or ecosystem types that are affected only by climate change, not in conjunction with sea-level rise. Climate warming effects on mangroves are likely to be beneficial, increasing mangrove productivity and biodiversity, hence the incorporation of climate models into a mangrove climate change vulnerability assessment becomes redundant, as mangroves are not vulnerable to climate warming. However, the effects of relative sea-level rise are likely to be negative or even severely detrimental to mangrove ecosystems, hence the inclusion of relative sea-level trends for mangrove sites are vital for the vulnerability assessment.

Changes in sea level (Figure 1) can result from variation in the volume of ocean water (eustatic change) or adjustment movement of the land, continental shelf or ocean floor (isostatic change). Isostatic movement can include subsidence caused by sediment loading which commonly occurs at the world's large deltas, as well as tectonic movement at plate boundaries. A coastal location will experience relative sea-level change or stability owing to a combination of some of these factors.

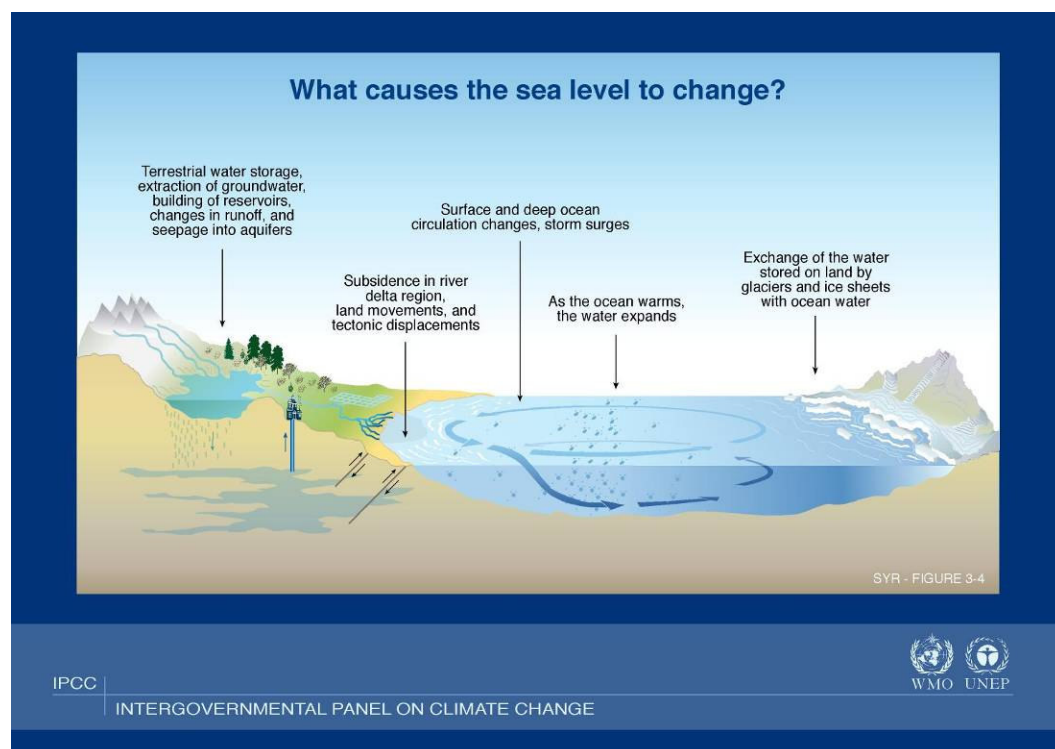


Figure 1. Causes of relative sea-level change (from IPCC, 2007).

The IPCC 4<sup>th</sup> Assessment projected rates of global eustatic sea level rise of 0.18-0.59 m by 2099 (1.5-9.7 mm a<sup>-1</sup>) (IPCC, 2007). Inter-tidal mangroves are extensively developed on sedimentary shorelines, where accretion determines their ability to keep up with sea-level rise. These sea-level rise projected rates mostly exceed mangrove accretion rates (Cahoon et al., 2002).

The rise and fall of land due to tectonic activity, isostatic readjustment of the Earth's crust following post-glacial redistribution of ice and water, and the eustatic changes in sea-level all result in greater or smaller changes in sea-level at the local scale (Houghton, et al., 2007). This 'relative sea-level change' is a combination of the change in globally averaged sea-level and regional and local factors and is measured at a tide gauge (Gilman et al., 2008). Differences in local tectonic processes, coastal subsidence, sediment budgets, and meteorological and oceanographic factors between the mangroves and the tide gauge may create additional variability (Gilman et al., 2008). Many islands in the Pacific region including Fiji have diverse tectonics, with differing relative sea-level trends (Pirazzoli, 1991; Emery and Aubrey, 1991; Ellison, 2010).

As mangroves establish between mean tide and mean high water, the elevation of their surface substrate relative to sea-level is critical to their survival. The ability of mangroves to respond to rising sea levels depends primarily on whether sedimentation rates can keep up with rates of sea level rise and what barriers are in place, such as roads and infrastructure, which may prevent their landward migration. Sedimentary accretion is a result of both autochthonous peat formation and allochthonous mineral sediment accumulation.

Sedimentation sources and rates influence vegetation resilience with rising sea level. Sediment losses include untrapped river sediment, longshore transport down the coast, mangrove litter outwelling, and relative sea-level rise (Ellison, 2009a). Sediment inputs relative to sediment losses determine whether the mangrove environment is erosional or accretionary.

The close relationship of mangroves with sea-level position makes mangroves particularly vulnerable to disruption by sea-level rise. When the rate of sea-level rise exceeds the rate of accretion, mangroves experience problems of substrate erosion, inundation stress and increased salinity. If sedimentation rates keep pace with rising sea-level then the salinity and frequency of inundation preferences of mangrove species zones will remain largely unaffected. However, if the rate of sea-level rise exceeds the rate of sedimentation then mangrove species zones will migrate inland to their preferred elevation and seaward margins will die back. Elevation of the ground surface can be raised under mangroves by the accumulation of vegetative detritus, both *in situ* and from matter brought in by tides and rivers, to form a mangrove peat or mud (Ellison, 2000).

River and tide dominated mangroves, together with mangroves with allochthonous sedimentation, are expected to have a better chance of survival and will potentially keep up higher rates of sea-level rise of (Ellison, 2009a) as they can receive greater amounts of sediment to compensate for rising sea-levels (Perry and Taylor, 2007). Mangrove species composition will also affect the ability of the ecosystem to respond to rising sea-levels with different species zones having different rates of

sedimentation (Krauss et al., 2003) and different individual species requiring different time frames to colonize new habitats. This may result in faster colonizers outcompeting slower colonizers and becoming more dominant (Lovelock and Ellison, 2007).

In conditions of sedimentation surplus, mangroves colonise seaward either into bays especially offshore of river mouths or over reef flats. In conditions where relative sea-level rise exceeds sediment accretion rates, mangroves die back from the seaward edge and retreat landward. This is demonstrated from the extensive coastal swamps of SW Papua (Ellison, 2005, 2009a). Sediment supply determines mangrove ability to keep up with relative sea-level rise.

Given that mangroves generally grow between mean sea-level and mean high water (Ellison, 2009a), their sedimentary records have been used as precise sea-level indicators. Comparing present trends in species and communities with palaeo-ecological records of past extents provides long-term records of how they may respond to climate change (Hansen et al., 2001; Hansen and Biringer, 2003).

### **1.1 Tide gauge records**

Measurement of present day sea-level change is by two different techniques, tide gauges and satellite altimetry (Bindoff et al., 2007). Tide gauges provide sea level variations with respect to the coastal land on which they lie, which is the information needed for mangrove climate change vulnerability assessment.

The AusAID SEAFRAME tide gauges have been established in the Pacific for less than two decades, including one at Lautoka in Northern Viti Levu installed in October 1992. These records are too short for a reliable long-term estimate of change in mean sea level, but will prove valuable in decades to come. The 14 year Lautoka record to 2006 showed a rate of relative sea-level rise of  $2.7 \text{ mm a}^{-1}$  (Hall, 2006). There is a longer term tide gauge at Suva, where a 24.8 year record to 2006 showed a rate of relative sea-level rise of  $3.99 \text{ mm a}^{-1}$  (Hall, 2006). This record however has gaps in the sea-level data, and the character of the record is somewhat different from nearby locations, calling into question the datum reliability of this gauge (Church et al., 2006). The difference could however be due to local tectonic movement, reviewed in the next section.

Global sea-levels after a long period of stability showed rise last century of  $1\text{-}2 \text{ mm a}^{-1}$  (Church et al., 2004), and analysis of regional trends showed  $0\text{-}5 \text{ mm a}^{-1}$  rise for Fiji from Topex/ Poseidon satellite altimeter data.

### **1.2 Geographical setting and regional sea-level trends**

Figure 2 shows the location of the Fiji, and the expected Late Holocene sea-level curve that for this region, as reconstructed from a number of proxy sea-level records (Pirazzoli, 1991).

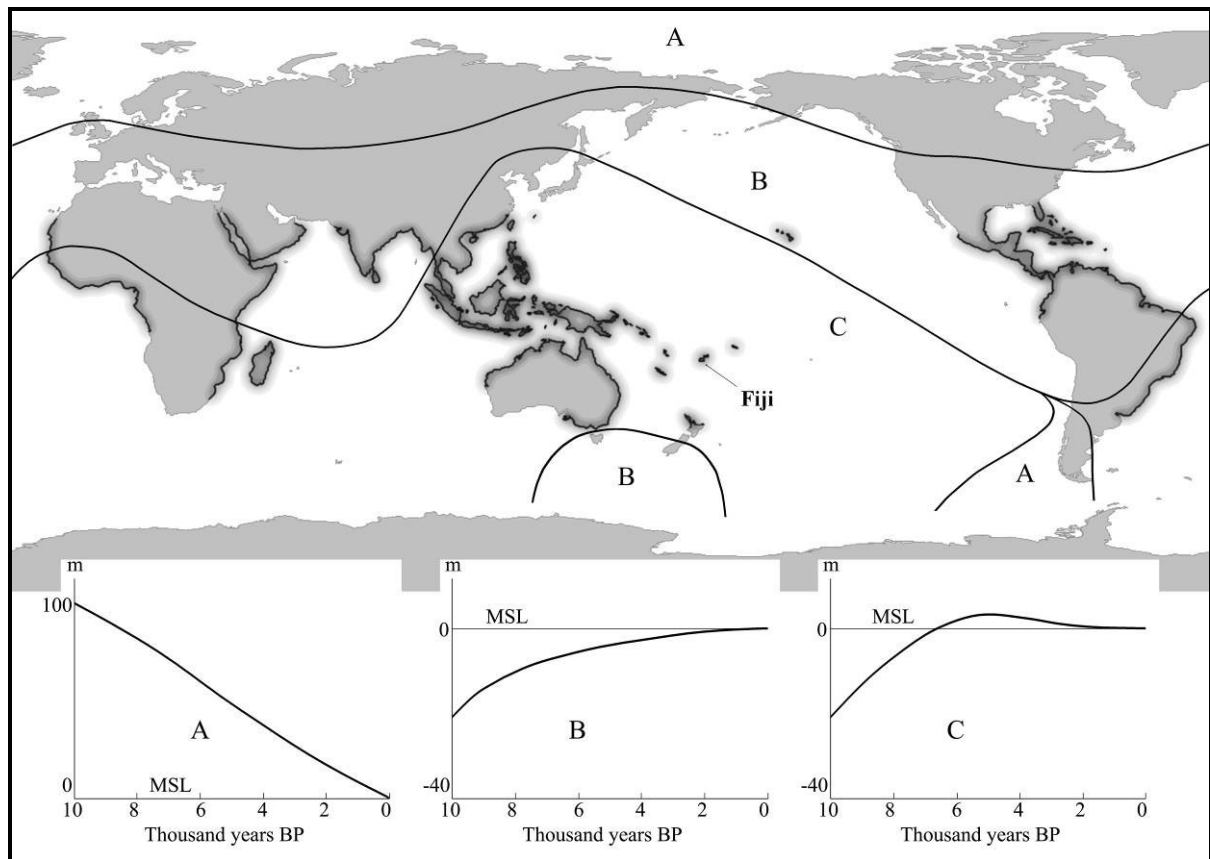


Figure 2. World distributions of mangroves (bold coastlines) and Holocene sea-level curve types (adapted from Ellison, 2009a).

The divergent plate boundary of the East Pacific Rise lies to the east of the Pacific Island region and sources the Pacific tectonic plate (Ellison, 2009b). The Pacific tectonic plate subducts beneath the Australian plate to the east of the main islands of Tonga and Fiji, hence tectonic movement is a factor in relative sea-level trends of these islands (Ellison, 1989; Ellison, 2010). Fiji was formed from uplifted crust over 40 million years ago and the two larger Fijian islands are mountainous with peaks up to 1300 metres and have small high gradient river catchments that discharge into coastal mangrove areas.

The recent tectonic movement of Fiji has been described by Nunn (1990a) and Nunn and Peltier (2001), from the dating of sea-level indicators mainly of coral micro-atolls, or marine shell, showing that many islands are either rising or subsiding. Hence, direct application of global sea-level projections is inappropriate in Fiji. Nunn and Peltier (2001) revised the initial assessment of Nunn (1990a), dividing Fiji into tectonic areas (Figure 3), and reviewed and synthesised evidence to identify Holocene subsidence or uplift, summarised in Table 1. Nunn and Peltier (2001) have shown the north coast of Viti Levu to be subsiding whilst the north coast of Vanua Levu is uplifting (Nunn and Peltier, 2001). The diverse tectonics of the region will result in differential mangrove responses to global sea level rise. Studies on Viti Levu have shown Holocene sea-levels to be near the present at about 5,600 years BP (before present) (Matsumoto et al., 1990), while a 0.7- 0.8 m fall in sea-level, accompanied by rapid cooling, affected the entire Pacific Basin around 700 years

before present (Nunn, 2007).

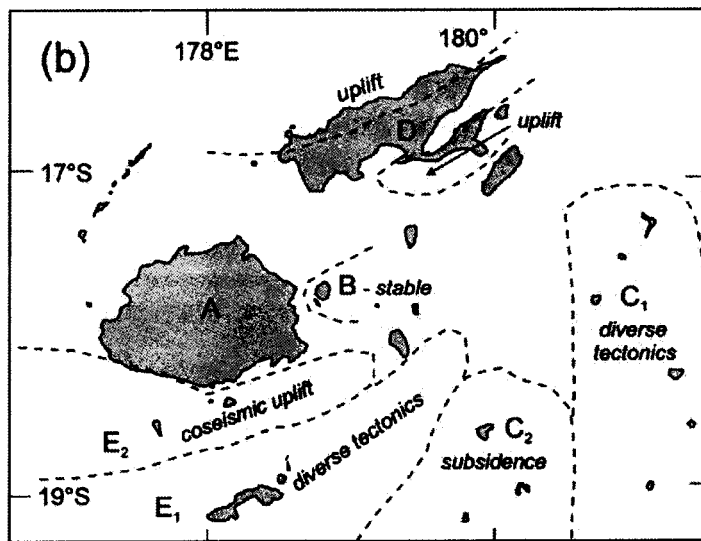


Figure 2. Tectonic divisions of Fiji (from Nunn and Peltier, 2001).

Tectonic Region (Figure 2)	Area	Holocene tectonics
A	Viti Levu	North coast subsiding South coast stable
B	Ovalau, Motoriki	Stable
C	Lau Yasa Yasa Moala Vanuabalavu	Unstable Subsiding Subsiding
D	Vanua Levu	North coast uplifting Cadaudrove peninsular uplifting
E	Kadavu, Vatulele / Beqa	Unclear

Table 1. Holocene tectonic movement of different areas of Fiji identified in Figure 2, from Nunn and Peltier (2001).

These tectonic trends can be used to infer the differential impacts of projected global sea-level rise. Areas that are stable such as the south coast of Viti Levu, Ovalau and Motoriki will experience the rates of sea-level rise predicted globally. Areas subsiding such as the north coast of Viti Levu and islands of the Lau group such as Yasa Yasa Moala and Vanuabalavu will experience greater relative sea-level rise. Areas uplifting such as the north coast of Vanua Levu will experience less or negligible relative sea-level rise. For mangrove climate change vulnerability assessments, the

rates of relative sea-level change need to be established quantitatively.

While there is some differential movement of islands within some of the above Fijian tectonic sub-regions. Most Pacific Islands experienced a higher sea-level stand in the mid-Holocene, owing to regional hydro-isostatic changes caused by post-glacial deformation of the mantle. In Fiji this is modelled at 2.1 meters above present (Nunn and Peltier, 2001), and occurred about 3000 to 6000 radiocarbon years before present (Dickinson, 2001). In the case of Vanua Balava in the Lau group, palaeo-shoreline evidence of this highstand now occurs at present sea-level, showing this island is subsiding at a rate of 0.5 mm a<sup>-1</sup> (Dickinson, 2001). This review also infers that Ovalau and Vanua Levu are subsiding at less rapid rates.

Nunn (1990b) used interviews with elderly people to infer sea-level rise over the last century at all of 16 coastal settlements in Fiji: 4 villages on Beqa (Table 1, region E), 2 on Gau (Table 1, region E), 2 on Lakeba (Table 1, region C1), 6 on Viti Levu (Table 1, region A), and 1 on each of Matuku and Totoya (both in Table 1, region C2). One of the few shorelines which previously was thought to be stable is the northern shore of Viti Levu, where large mangrove deltas and a complex pattern of offshore reefs suggested Late Holocene sea-level stability (Nunn, 1998). However, interviews with elderly residents at Namoli and Natunuku both in the north-west shore of Viti Levu indicated that both have noticed sea-level rise during the last century (Nunn, 1990b). Nunn and Peltier (2001) revised Nunn (1998) and this area is now thought to be subsiding. There may be enhanced subsidence in deltaic areas, owing to shelf loading by sediment (Nunn and Peltier, 2001). This study reconstructs relative sea-level from a deltaic area on this coast at Lomawai.

Fiji's climate is heavily influenced by the South East Trade Winds with a distinct summer wet season and strong orographic influences on rainfall distribution across the higher islands of Viti Levu and Vanua Levu (Fiji Meteorological Service, 2010). The region is tropical with maximum temperatures between 26°C to 31°C. Annual rainfall on the main islands is between 2,000 and 3,000 mm on the coast and up to 6,000 mm in the mountains, with a leeward rain-shadow (Fiji Meteorological Service, 2010). The smaller islands typically receive less rainfall, depending on their location and size, with annual precipitation ranging from 1,500 to 3,500 mm. Tropical cyclones occur between 10-25 degrees south of the equator when ocean surface temperatures are warm, causing damage and flooding wetlands (Fiji Meteorological Service, 2010). The El Nino Southern Oscillation (ENSO) creates climate variations every 2-5 years, particularly affecting winds and precipitation in the region and creating drought conditions in some areas (Meehl, 1996).

Viti Levu is a high volcanic island, with the highest peak rising to 1,324 metres, and has an area of 10,389 km<sup>2</sup>. The combination of topography and prevailing South East Trades results in an orographic effect. The mountain ranges running through the centre of the island create a distinct wet climatic zone on the eastern windward side, and a dry climatic zone on the western leeward side (Fiji Meteorological Service, 2010).

Vanua Levu lies 64 km to the north of Viti Levu and has an area of 5,587 km<sup>2</sup> with the highest point at an altitude of 1,111 metres. The island is divided along its length by a mountain range with orographic rainfall resulting in a wet southern coastline and



drier northern area (Fiji Meteorological Service, 2010).

### 1.3 Mangrove species present

Fiji's mangrove flora consists of seven mangrove species, and a hybrid (Ellison, 2009b). Mangrove areas are dominated by three species from the family Rhizophoraceae: *Bruguiera gymnorhiza*, *Rhizophora stylosa* and *Rhizophora samoensis*. *Rhizophora stylosa* and *Rhizophora samoensis* have crossed to create the sterile hybrid *Rhizophora x selala* which is only found in Fiji and New Caledonia, with Fiji having the greatest area (Watling, 1985). Other less common mangrove species include *Xylocarpus granatum*, *Lumnitzera littorea*, *Excoecaria agallocha*, and *Heritiera littoralis* (Smith 1981, Watling 1985, Pillai 1990). The mangrove fern *Acrostichum aurum* is also widespread. Zonation of mangrove species from sea to land is shown in Figure 3.

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<b>Sea</b>	<b><i>Rhizophora stylosa</i></b>	<b><i>Rhizophora samoensis</i></b>	<b><i>Bruguiera gymnorhiza</i></b>	<b><i>Excoecaria agallocha</i></b>	<b>Land</b>
		<b><i>Rhizophora x selala</i></b>		<b><i>Heritiera littoralis</i></b>	
				<b><i>Xylocarpus granatum</i></b>	

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Figure 3. Mangrove species zonation of Fiji.

Mangrove associate species present include *Derris trifoliata*, *Vitex trifolia*, *Hibiscus tiliaceus*, *Leuceanea leucocephala*, *Paspalum discitichum*, *Thespesia populnea*, *Coccoloba nucifera*, and *Pandanus sp.* Fiji's mangrove fauna include crabs, prawns, a mangrove lobster, shellfish, fish, sharks, rays, eels, and other invertebrates, plus a few terrestrial animals which live in the forest: birds, flying foxes, other small mammals, and insects (Thaman and Naikatini, 2002).

### 1.4 Approach and objectives of this study

Stratigraphic cores and palaeoenvironmental study can be used to reconstruct Late Holocene relative sea-levels. Long term net sedimentation rates can be calculated from calibrated radiocarbon dates of core stratigraphy (Ellison, 2008). Pollen records of mangrove species zones can be used as a finite sea-level indicator, which means they can accurately reconstruct a former sea-level rather than using directional indicators which are more qualitative (Ellison, 2008; 2009a).

This study uses mangroves as a finite indicator of sea-level position, given different mangrove species have specific requirements of frequency, period and depth of

inundation, creating mangrove species zonation (Figure 3). The deposition of pollen below mangrove canopies has been shown to reflect local species zonation (Ellison, 1989; 2005) and elevations of these zones can be used to interpret past sea-levels from stratigraphic pollen patterns. *Rhizophora* and *Bruguiera* have been shown to be particularly sensitive indicators (Ellison, 2005).

The anaerobic wet environment of mangrove sediment allows for the long-term preservation of records such as pollen. Deposits which have been exposed tend to oxidise meaning that land-based cores are often more fragmentary than offshore cores (Ellison, 2008). The interpretation of event continuity can be difficult as a result of bioturbation by crabs and with the erosion of mangrove sediment during rising sea-level, resulting in the loss of record with the removal of mangrove substrate and some deposition offshore.

Below canopy mangrove pollen deposition has been shown in many studies to reflect local species zonation, particularly percentage abundance diagrams as opposed to pollen concentration (Muller, 1964; Spackman et al., 1966; Woodroffe et al., 1985; Chappell and Grindrod, 1985; Grindrod, 1985; Grindrod, 1988). Ellison (1989, 1993; 2005) demonstrated how elevations of modern species zones can be used to interpret a high resolution sea-level reconstruction from stratigraphic mangrove pollen patterns.

Several studies of pollen in surface samples within the mangrove ecosystem have showed that there is a high *Rhizophora* proportion in and immediately adjacent to the *Rhizophora* zone (Muller, 1959; Cohen and Spackman, 1977), and this can be utilized as a sea-level indicator. Wijmstra (1969), used modern surface samples from mangroves to interpret fluctuations of sea-level from the Cretaceous to the Plio-Pleistocene in Surinam, identifying a 90% proportion of *Rhizophora* as a *Rhizophora* stand, and a 30% proportion as immediately adjacent to a *Rhizophora* stand, such as a seaward mud flat. Bartlett and Barghoorn (1973) used similar proportional representation to interpret the Holocene sea level transgression from Panama, that between 45% and 95% of *Rhizophora* plus *Avicennia* represents a mangrove swamp of these species, and 45% to 10% *Rhizophora* pollen, declining to less than 10% represents sediments immediately landward of mangroves. Extensive work in tropical Australia then fully established the value of pollen analysis of mangrove sediments to environmental reconstruction. High proportions of mangrove pollen were found to indicate a mangrove environment, declining to 50% or less immediately adjacent (Grindrod and Rhodes, 1984, Grindrod, 1985; 1988; Chappell and Grindrod, 1985; Woodroffe et al., 1985, 1987; Behling et al., 2001; Ellison, 2005).

The objectives of this study are to show recent sedimentation rates and mangrove vegetation changes of two significant mangrove areas in Viti Levu and Vanua Levu, to provide a reconstruction of relative sea-level trends for the Late Holocene (last few hundred years).

## 2.0 Methods

### 2.1 Study Sites

The two study sites are part of the WWF Fiji Country Program which has been working with local communities in the areas since 2000, facilitating workshops to assist in developing management strategies to ensure the sustainable use and conservation of mangrove resources (Thaman and Naikatini, 2002) (Figure 4). They are two of the three GEF project sites, while the third, Verata, has some stratigraphic and pollen analysis results already available for that section of the coast (Southern, 1986; Yonekura, 1990).

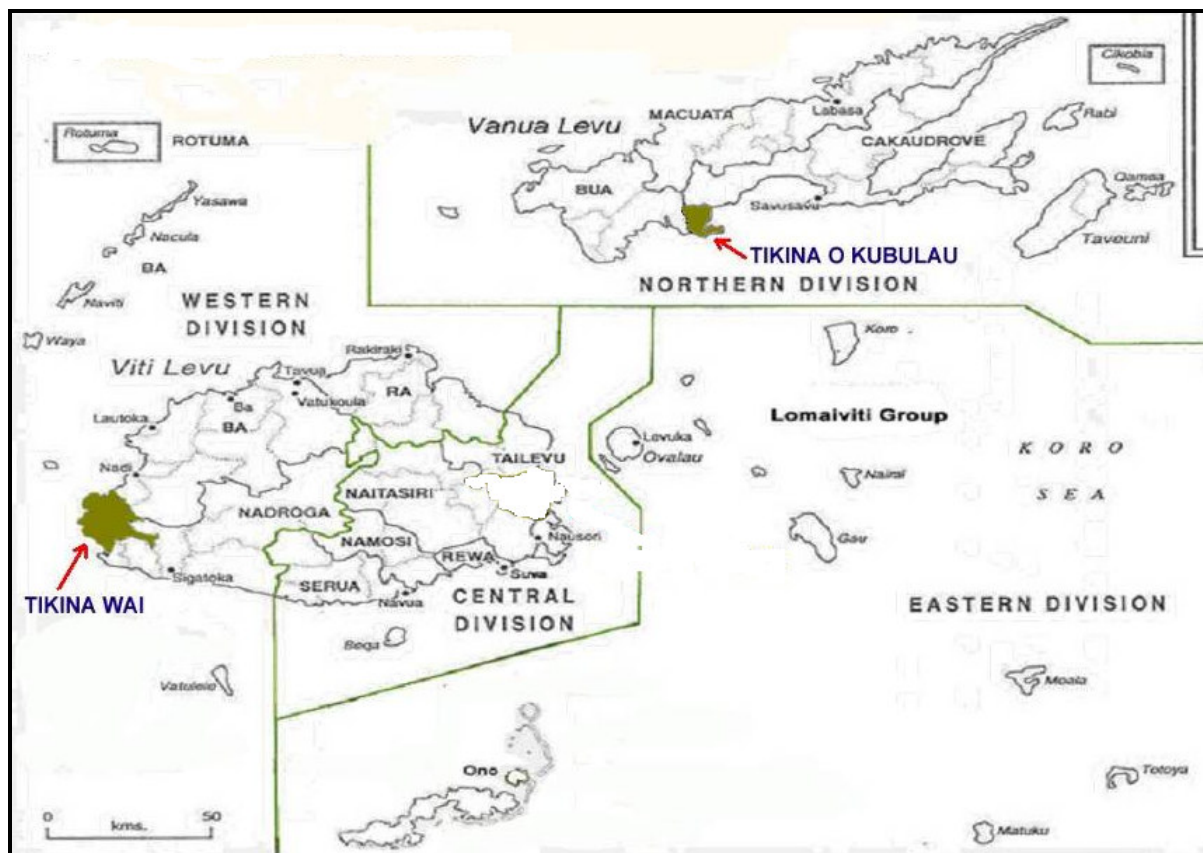


Figure 4. Project study sites (WWF South Pacific Program)

The study site at Lomawai is located on the western dry leeward side of the main island of Viti Levu. Tikina Wai has a 45 km long district coastline, comprising sand and mudflats, submerged fringing reefs, channels, reef flats and patch reefs, extending offshore some 4-6 km between coast and reef (WWF, 2004). The Kubuna River estuary enters the reef lagoon to the north of the major mangrove area, while a small creek drains its centre. On landward margins large salt pans occur.

The undulating hills inland are dominated by 'Talasiga grassland' along with productive landscapes of sugarcane and tropical pine (WWF, 2004). The area comprises Oligocene/mid-Miocene sediments and volcanics with predominant soil types being clays and a mixture of sands and loams in the lower lying areas (WWF,

2004). The area is a major sugar producing area which is an important crop in the Fijian economy, with changes in the local climate and adverse impacts on the land severely impacting local farmers and productivity. In addition, the majority of local people are semi-subsistence farmers and fishermen dependent on land and marine resources for food security and income. The area's vulnerability to rising sea level is also increased as a significant proportion of the area's population, infrastructure and prime crop land are located on low lying coastal land (WWF, 2004). Four villages in Tikina Wai, Lomawai, Kubuna, Nakorokula, and Tau, are located on the coast, and two are inland: Bavu and Navutu. The population density for Tikina Wai is 23 persons per km<sup>2</sup> (WWF, 2004).

Between 1967 and 1994 about 11 hectares of mangroves and 3 hectares of salt ponds have been lost in the area (Thaman and Naikatini, 2002) due to human impact. In the 1940's large mangrove trees were cut for firewood for the production of limestone at the quarry in Tau (Thaman and Naikatini, 2002). Today the area contains about 441 hectares of mangroves. The mangroves are traditional fishing/food collecting areas for the villagers of Tau, Lomawai, Nakorokula, Bavu, Navutu and Kubuna and these villages also form part of a group of communities on Viti Levu which supply *Bruguiera* bark and dye to Vatulele for the making of tapa or masi. There is a general understanding that the *Bruguiera* bark harvesting technique is damaging to the health of the trees (WWF, 2000). In addition, mangrove wood is harvested for firewood and construction materials, mainly for subsistence use. Mangrove fauna in the area includes crabs (*Scylla serrata*, *Metapograpsus messor*, *Cardisoma carnifex* and *Uca* species), mud lobster (*Thalassina anomala*), molluscs (*Crassostrea mordax*, *Littorina scabra*), fish (*Lutjanus argentimaculatus*, *Upeneus vittatus*) and the common mudskipper (Periophthalmidae family). Birds, flying foxes and a few other mammals also use the mangrove areas. Threats to mangroves in Tikina Wai include reclamation for commercial, industrial and residential development, overexploitation of products as a result of increased coastal populations and commercialization of products, and drainage and dredging activities (Thaman and Naikatini, 2002). Three mangrove reserves are today managed by a Marine Resource Management Committee with representatives from the 6 local villages (Ellison, 2009b). These three protected areas (tabu in Fijian) are Lomawai Reserve, Bole Reserve and Lotonaluya Reserve (WWF, 2004). The Mangrove Area Management Plan provides a broad guide by which decision makers can ensure the sustainable use of the area to meet local needs for food, income and cultural maintenance.

The study site for this project was located within Lomawai Reserve, adjacent to Lomawai village (Figure 5). The reserve is about 1.4 km wide at its maximum width and 1 km in length seaward of the railway track. Mangroves in the area typically consist of extensive salt pans and areas of stunted *Rhizophora* (about 2 metres in height) fringing the salt pan areas. Growth is more vigorous along the edges of the creeks and rivers, with dominant species such as *Rhizophora samoensis* and *Bruguiera gymnorrhiza* growing to heights of 6 metres. The landward edge of the salt pan includes species such as *Xylocarpus granatum* and *Excoecaria agallocha*, while the coastal fringe of the reserve is dominated by *Rhizophora stylosa* seaward and *Rhizophora samoensis* inside this (Thaman and Naikatini, 2002). The *Rhizophora* is characterised by a closed canopy with a mangle of trunks, branches and prop roots making access difficult. Annual rainfall averages around 2,000 mm (Fiji

Meteorological Service, 2010).

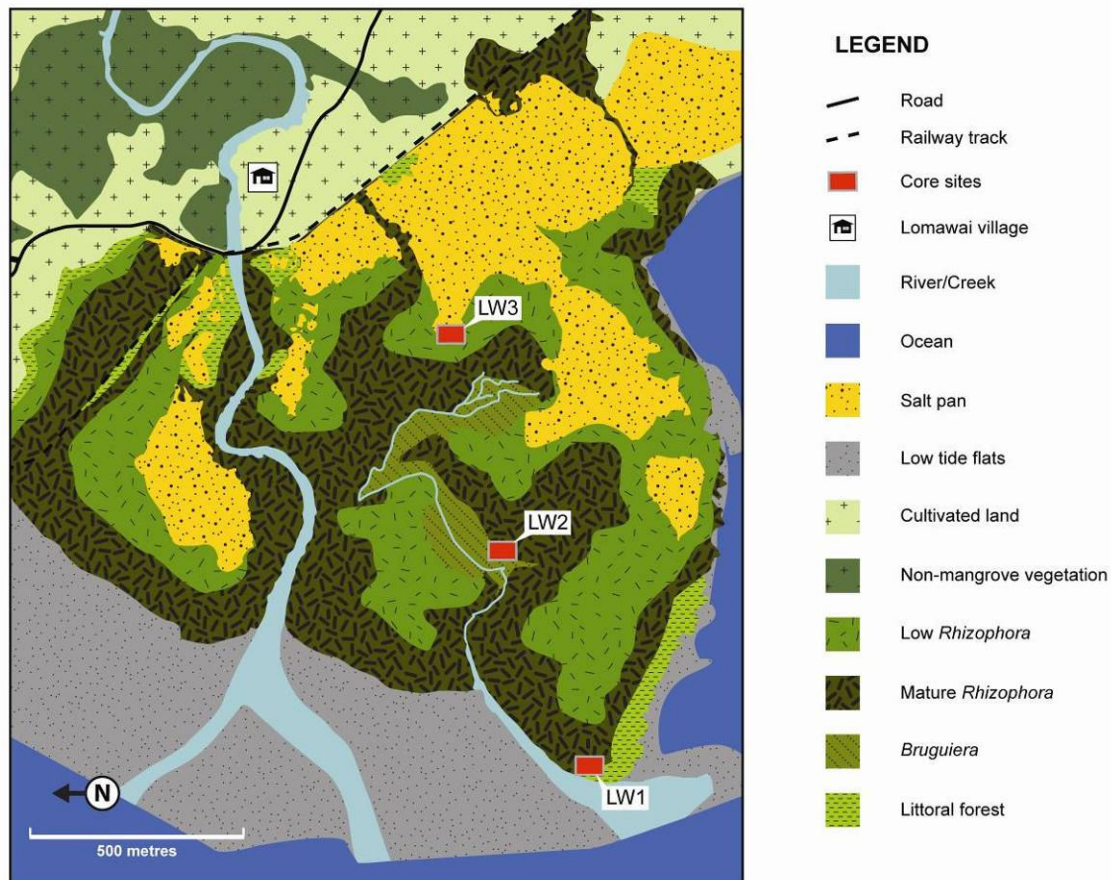


Figure 5. Map of Lomawai Reserve showing location of core sites (adapted from Thaman and Naikatini, 2002)

The second study site was located on the South Coast of Vanua Levu in the Kubulau region, adjacent to Ravi Ravi village. The Kubulau district comprises 100.3 km<sup>2</sup> of land with 69 km of coastline and 2 islands: Namenalala and Navatu (WCS, 2009). There are 10 villages in the region with approximately 1,000 people and high rainfall, generally greater than 3,200 mm annually (Fiji Meteorological Service, 2009). Land use comprises natural forest (63%), pine and coconut (10%), grasslands (5%), secondary forest (3%), and intensely cultivated areas (1%) (WCS, 2009). The mangrove area (Figure 6) is characterized by *Rhizophora samoensis* and *Rhizophora stylosa* on the seaward edge (about 10-15 m) with a landward transition to monospecific *Bruguiera*. Evidence of a past lava flow limits the distribution of mangroves along parts of the coastline (Figure 7). In January 2009 the World Conservation Society released a report on mangrove change in the Kubulau area using historical mapping assessment and satellite imagery by the Fiji Department of Forestry. Results showed a net decline in mangrove areas of approximately 200 hectares between 1954 and 1994 (WCS, 2009).



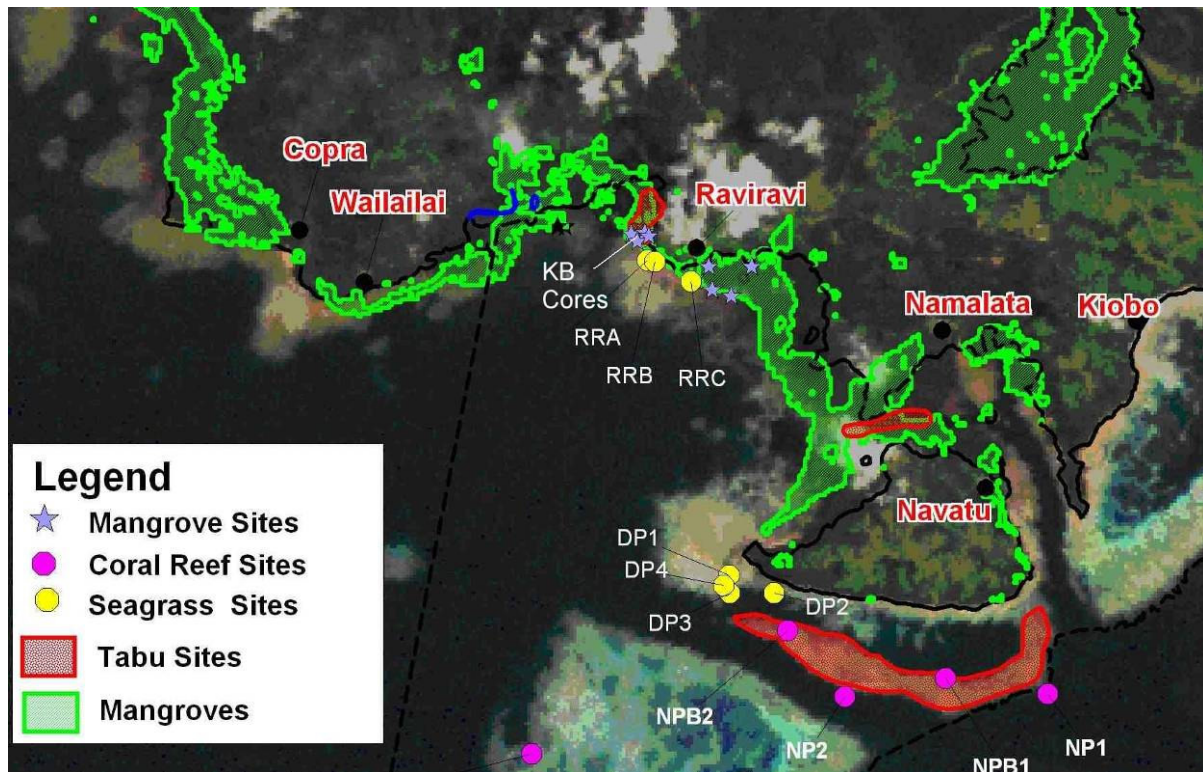


Figure 6. Location of KB Cores in the mangrove Tabu site west of Raviravi Village, Kubulau (adapted from a WCS image produced for this project).



Figure 7. Photograph showing lava flow under mangroves at Kubulau (Picture B. Morrison).

## 2.2 Coring Techniques and Relative Elevations

Coring sites in the Lomawai Reserve at Tikina Wai corresponded with permanent mangrove monitoring stations established for the project along a transect from sea to land through the major mangrove area (Figure 5). Cores were taken at three locations along this transect, reducing the influence of local land-based edge effects, and elevations of mangrove species zones were surveyed. A Hiller Corer (Figure 8) with a 1 m sample chamber length and 4 cm diameter was used as elevation was critical and these sidewall sampling corers ensure no compaction (Ellison, 1989). A Russian Peat Corer (Figure 9) with a 50 cm sidewall sample chamber length and 5 cm diameter was also used to core through sandier stratigraphy not suitable for the Hiller Corer. The corer was dismantled and washed following each metre or half metre cored to prevent any sample contamination and the corers were washed before the cylinder was opened to prevent contamination from upper layers.



Figure 8. Hiller corer at core site LW3 (Picture B. Morrison)





Figure 9. Russian peat sampler at core site LW3 (picture J. Ellison).

Elevations at Lomawai were determined by installation of a temporary tide gauge (Figure 10) and, using a tripod mounted level, surveyed relative to the height of the level railway line (from here on referred to as Elevation Datum). Sites through the mangrove swamp were measured in depth relative to tidal sea water levels, and these were contemporaneously read from the tide gauge during rising to high tide. Sites above water level at the time of measurement were surveyed relative to water level using a tripod mounted level, and the tide gauge contemporaneously read.





Figure 10. Temporary tide gauge at Lomawai village.

Two core sites were analysed at Kubulau (Figure 6) one 15 m from the seaward edge of the mangrove forest (KB1) and the other 60 metres inland on the edge of the river channel in *Bruguiera* forest (KB2). Due to the dense root structure of the mangroves at both Kubulau sites the Hiller Corer was solely used owing to its smaller diameter. As no tidal datum was available in the area the relative elevations of the two Kubulau sites were determined relative to the clear high tide markings on the mangrove trunks (Figure 11).



Figure 11. High tide mark on *Bruguiera* trees at core site KB2 in the Raviravi Tabu mangrove area, Kubulau (Picture: B. Morrison).

Cores were sub-sampled at 10 cm intervals. Sample contamination was prevented by washing the corer each time used, also wiping spatulas used for sub-sampling. To avoid contamination from upper layers, the sampler was washed off before opening the cylinder. Colour of stratigraphic units was determined in the field by comparison with Munsell Soil Colour Charts.

### 2.3 Radiocarbon Dating

Samples collected for radiocarbon dating and analysis were removed from the corer using a spatula, placed on aluminium foil and wrapped on site in individual plastic bags to avoid contamination. They were sent to Beta Analytic Incorporated in Florida, USA for Accelerated Mass Spectrometry (AMS). Radiocarbon dating is a method of dating material which has been buried from contact with any decaying process. The AMS method of dating is good for smaller samples and fragments, such as wood and leaves, and provides tighter error margins than conventional dating (Ellison, 2008). The samples were pre-treated to eliminate secondary carbon components. First they were crushed and dispersed in deionized water and then given hot HCl acid washes to eliminate carbonates and NaOH alkali washes to remove secondary organic acids. The alkali washes were followed by a final acid rinse to neutralize the solution prior to drying. Depending on each sample, different chemical concentrations, temperatures, exposure times, and number of repetitions were applied with each chemical solution neutralized prior to application of the next (Beta Analytic Inc., 2009). During these serial rinses, mechanical contaminants such as associated sediments and rootlets were eliminated. Radiocarbon dates are

corrected for fractionation error using the  $^{13}\text{C}:^{12}\text{C}$  ratio determined for each sample. Dates are reported in measured radiocarbon years before present (BP), and conventional radiocarbon years BP based on the Libby half-life of 5568 years (Beta Analytic Inc., 2009).

Radiocarbon dates were corrected for fractionation error using the  $^{13}\text{C}/^{12}\text{C}$  ratio determined for each sample. They are reported in conventional radiocarbon years before present (BP), and calibrated to calendar years using standard calibrations. Calibrations of radiocarbon age determinations were applied to convert BP results to calendar years, with short term differences between the two caused by fluctuations in the heliomagnetic modulation of the galactic cosmic radiation, as well as large scale burning of fossil fuels and nuclear devices testing (Beta Analytic Inc., 2009). The parameters used for the corrections were from analyses of hundreds of samples taken from known-age tree rings of oak, sequoia and fir up to about 10,000 BP and calibrated (Talma and Vogel, 1993).

## **2.4 Analysis of Pollen**

Samples for pollen analysis were taken from cores at 10 cm intervals and stored in cool conditions in Ziploc bags. They were taken by Australian Quarantine at Sydney Airport for gamma irradiation sterilization, as arranged by a University of Tasmania Quarantine Permit. Gamma irradiation kills bacteria by breaking down bacterial DNA and inhibiting bacterial division. The samples were exposed to gamma rays (electromagnetic radiation of very short wave lengths) and, as the process is not reliant on humidity, temperature, vacuum or pressure, the sample bags remained intact, the seals were not stressed, and the samples remained moist. At all stages samples were kept in relatively cool conditions to prevent drying out.

Pollen samples were then prepared at the University of Tasmania in accordance with methods outlined in Ellison (2008). Pollen was concentrated, along with other resistant materials such as charcoal, sponge spicules and cysts. Cross contamination between samples was prevented using separate stirring sticks for each sample and strict washing of sampling containers between samples. From each sample a 1 cm<sup>3</sup> sub-sample was placed in a 15 ml polypropylene test tube and two exotic pollen tablets added. This step in the process is to compensate for the loss of fossil pollen during laboratory preparation and is based on the assumption that exotic pollen will be lost at an equivalent rate to fossil pollen.

Calcium carbonate was removed by the addition of 10% HCl and the sample stirred with a wooden applicator stick while placed in a warm water bath. Liquid was then removed by centrifuging at 3500 rpm for 5 minutes and the supernatant decanted into the chemical waste bin. Distilled water was then used to wash samples. Humic compounds were then removed using 10% NaOH and test tubes placed into a hot water bath for 15 minutes while being stirred and distilled water added to prevent increased concentration by evaporation. The sample was then washed repeatedly until the supernatant ran clean. This sediment was now dispersed as a result of the NaOH treatment and was passed through a 150 µm sieve to remove large organic fragments before reconcentration. Hydrofluoric acid (HF) was then used to remove silicates from river sediment with samples left in HF overnight at room temperature.

The samples were again centrifuged, the HF decanted and samples washed.

The pollen wall ornamentation was then made visible by acetylosis. Samples were washed in glacial acetic acid to eliminate water with which acetic anhydride reacts violently (Ellison, 2008). Then a 9:1 mix of acetic anhydride and concentrated sulphuric acid was added and test tubes placed in a hot water bath for up to 10 minutes. Samples were then washed again with glacial acetic acid followed by distilled water. 3% bleach was then added for oxidation as mangrove vegetative matter is particularly resistant. This was diluted and removed according to the speed of the reaction and the sample washed. Towards the end of the procedure 50% ethanol was added for dehydration and then two drops of safranin stain, then 75% followed by 95% ethanol. Tertiary butyl alcohol was then added and test tubes centrifuged and decanted before being transferred to labelled glass storage vials in this alcohol. Silicone oil was added and vials left at 47°C to evaporate the alcohol and to leave the pollen preserved in silicone oil.

Samples were then mounted on slides using silicone oil, allowing the pollen to be turned over for identification, and pollen were identified by comparison with a reference collection. Results were plotted into pollen diagrams using TILIA and TILIAGRAPH. The relative representation of each taxon (percentage) was used to interpret these pollen diagrams as identification of a mangrove zone is by relative presence of taxa of different zones. The pollen diagrams show the relative representation of each mangrove taxon recorded in samples down each core as a percentage of the total pollen sum which includes mangrove taxa, non-mangrove trees and shrubs, ferns, herbs and aquatics. The number of exotic *Lycopodium* was also counted and, from this, absolute concentration of pollen in grains/cm<sup>3</sup> determined using the following equation:

$$\text{Concentration (grains/cm}^3\text{)} = \frac{\text{Total no. exotics added}}{\text{No. exotics counted}} \times \frac{\text{No. fossil pollen counted}}{\text{Volume of sub-sample}}$$

Broadly negative relationships between pollen concentrations and sedimentation rates are expected in allochthonous environments where high sediment input dilutes the pollen concentration.

## 2.5 Percentage Organic Determination

The remainder of each sample was air dried in a fume cupboard overnight to allow air circulation to dry the samples. They were then crushed and sieved using a 2 mm sieve and placed into crucibles in an air-circulation oven at 105°C. After cooling, the crucibles were weighed and the weight of each crucible with the sample was also weighed before being placed into a muffle furnace and left for 2 hours at 550°C. When cool the samples were transferred to a desiccator, cooled to room temperature and weighed. Percentage Organics based on loss-on-ignition was then determined using the following equation:

$$\text{Loss on ignition (\%)} = \frac{\text{weight loss (g)} \times 100}{\text{oven-dry weight (g)}}$$

## 3.0 Results

### 3.1 Elevations

Distinct mangrove zonations corresponding with micro-elevation were found within Lomawai Reserve with tall *Rhizophora* forests dominating the seaward edge from 1.9 to 2.6 m below elevation datum, a range of around 0.7 metres. *Bruguiera* dominant forests were found more inland, from 1.9 m below datum, and stunted *Rhizophora* occurred above this towards the salt flat/mangrove boundary which was at 1.6 metres below elevation datum. The survey results indicate an elevation range of 1.0 +/- 0.1 metres for mangroves in the Lomawai Reserve. These results are summarized in Table 2.

Site	Elevation (m)
LW3 core top	-1.53
Saltflat/ <i>Rhizophora</i> boundary	-1.60
<i>Rhizophora/Bruguiera</i> boundary	-1.9 +/-0.1
LW2 core top	-2.03
LW1 core top	-2.04
<i>Rhizophora</i> seaward edge	-2.6 +/-0.1

Table 2. Elevations of mangrove zones in the Lomawai Reserve (in metres below the Elevation Datum).

Owing to lack of elevation datums in the Kubulau area, core elevations were determined relative to each other by measurement from the high tide mark on trees (Figure 11). Results showed that the 0 level of the seaward core KB1 was 6 cm lower than the landward core KB2.



## 3.2 Stratigraphy

### 3.2.1 Lomawai

The stratigraphy of the Lomawai cores indicates sediment composed primarily of organic silty clay or mangrove peat with a number of shelly marine sediment lenses in all three cores and distinct sand lenses in LW2 (Figure 12). The marine lenses at 3-4 m below datum in all three cores line up well and may indicate a tsunami or storm event occurred, washing marine sediment across a normally finer textured mangrove swamp.

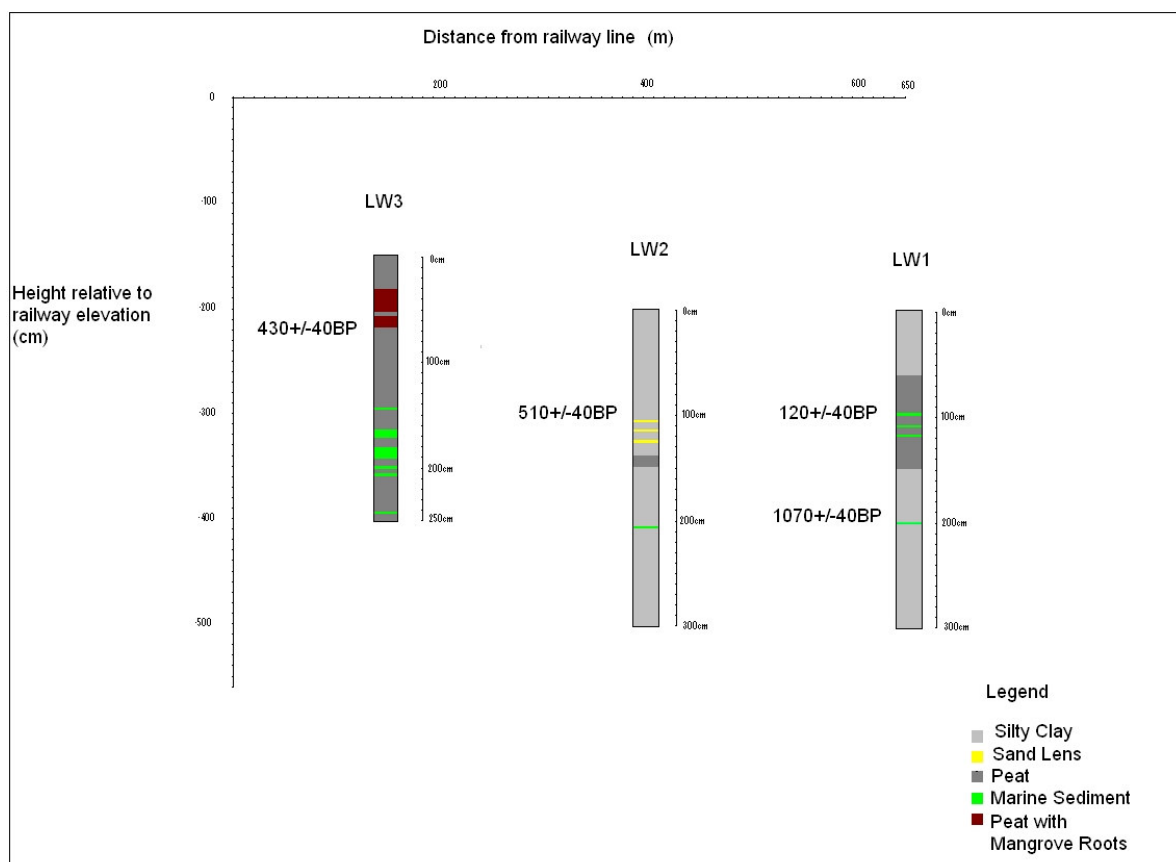


Figure 12. Core locations and relative elevations, Lomawai, Fiji

At the seaward edge site LW1 was a low, discontinuous storm ridge of sand and shingle, banked up against the seaward ridge of mangroves (Figure 5). The core site was located 10 m North-West of the sand edge and 30 m North-West of the chenier ridge. We cored down to 300 cm without hitting rock, indicating that the sediment was deeper still (Figure 12). The Hiller corer was used for the top 100 cm and from between 200-300 cm, while the Russian Peat Corer was used for the middle section due to the sand content in the sediment. A number of large *Rhizophora stylosa* were in the immediate vicinity, as well as occasional *Bruguiera* juveniles and 15 cm high crab mounds. The majority of the top 150 cm was an organic silty clay with sand, shell and coral grit, with a dark organic colour and occasional red mangrove root

debris (Munsell Soil Colour 10YR 2/1, black). Between 107-108.5 cm and 115-116.5 cm there were distinct peaty sand mix lenses and from 125-127 cm a clear sand layer without peat was present. There was a dark brown matting (10YR 3/4) at 140 cm with reddish mangrove fibres. At 150 cm there was an organic peaty silty clay with grit/sand contact (10YR 3/1, very dark gray) with a gradational change to 10YR 4/2 (dark grayish brown) at 185 cm where pale root fibres were apparent as well as red mangrove bark fragments. From 190-192 cm there was a distinct paler layer of silty clay without sand (10YR 5/1, gray) and again at 210-230 cm before a gradational change to an organic silty sand (10YR 4/1, dark gray) at 230 cm. At 285 cm the sediment became a dense silty clay with little grit/sand content (10YR 6/1, gray), and the core could have gone deeper with more extension rods.

Between core sites LW1 and LW3 at the central mangrove swamp core site LW2 was dense *Bruguiera* forest (Figure 5). The top 40 cm was a silty peat with high sand content (7.5YR 4/1, dark gray) before a gradational change to sediment with less sand and higher organic content (7.5YR 3/1, very dark gray), as shown in figure 12. From 30-50 cm there were small fibrous roots found and at 50 cm the sediment became a mottled grey silty clay with high fibrous material. At 70 cm the sediment became gritty with more sand (10YR 5/1, gray) before a gradational change to clay with fibrous material and shells (10YR 4/1, dark gray) at 100 cm. From 100-160 cm there were gradational changes between 10YR 3/1 and 10YR 4/1. Between 160-165 cm there was a grey lens (Gley1 8/5G, light greenish gray) with fibrous material and shell, with another apparent between 175-183 cm (Gley1 7/5G, light greenish gray), and another between 193-196 cm (Gley1 8/10gy) and 200-203 cm (Gley1 8/10GY, light greenish gray) where some coarse sand and red mangrove roots were also found. From 203-250 cm the mangrove root content material increased through a peaty sand (10YR 4/1, dark gray) and some grey mottling. There was another lens at 235 cm (Gley1 8/10GY, light greenish gray). Between 250-300 cm there were gradational changes between Gley1 8/10GY and Gley1 8/5GY with a mottled grey and peaty clay with some fibrous material. At the base of the core (300 cm) some shell was found, and the core could have gone deeper with more extension rods.

The landward margin core site LW3 was located on the edge of the landward salt pan which lies adjacent to the village of Lomawai, adjacent to low *Rhizophora* (Figure 5). The Russian Peat Corer was used for the top 50 cm and then the Hiller used for the remainder of the core. Between 0-60 cm there were gradational changes between dark grey (5YR 4/1) and reddish brown (5YR 5/4), as shown in Figure 12. At 60 cm there was a sharp contact to a dark grey silty clay (10YR 4/1) containing red mangrove root fragments. At 98 cm there was another sharp contact to grey clay (Gley 1 6/5G) with mangrove peat fragments still present and seagrass blades found. At 160 cm the material became coarser and a darker grey colour and between 168 cm and 178 cm there was a gradational change to a smoother clay. At 230 cm there was a gradational change with sediment becoming coarser and some shell fragments found. At 305 cm the core hit hard clay, and could not penetrate deeper.

### 3.2.2. Kubulau

There was a distinct zonation found in Kubulau mangroves with *Rhizophora* forests dominating the seaward edge before a transition to monospecific *Bruguiera* on the landward side of the mangrove swamp. In the river entrance that comes through the mangrove tabu area west of Raviravi village (Figure 6), core attempts in the seaward edge only penetrated 50 cm before hitting rock.

Core KB1 was taken about 15 m inside the seaward edge at the *Rhizophora/Bruguiera* boundary with 15 m tall *Rhizophora* to seaward and 15 m tall *Bruguiera* to landward. KB1 core 0 level was 6 cm lower in elevation relative to the 0 level of KB2 which was located further inland. The stratigraphy of the two Kubulau cores showed primarily peat and silty clay without any marine sediment or sand lenses (Figure 14).

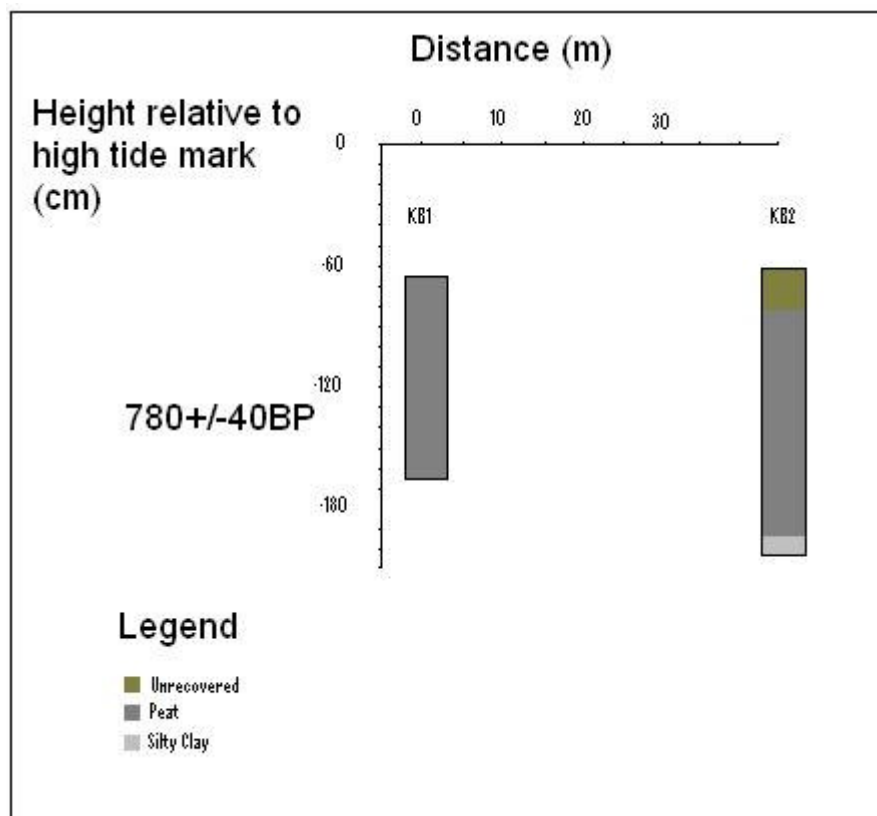


Figure 14. Core locations and relative elevations, Kubulau, Fiji

Core KB2 was located in closed canopy monospecific *Bruguiera* forest about 25 m high with numerous seedlings and saplings. The high tide mark indicated on the trees was 80 cm and the water depth at the time was 26 cm. The Hiller Corer was used for this core. The top 20 cm was very loose and not recovered, but by hand sampling was determined to be similar to the recovered material at 20 cm. Between 20 cm and 90 cm was a peaty silt mix without sand (10YR 2/1) and large roots were apparent at 85 cm, as shown in figure 17. From 90-100 cm the sand content increased and between 135 cm and 143 cm the sediment became a loose organic silty grey with grit (5YR 3/1), before hitting hard rock.



### 3.3 Radiocarbon dates and sedimentation rates

Radiocarbon dates from the four longer cores are shown in Table 3. All results showed  $^{13}\text{C}/^{12}\text{C}$  ratio results typical of mangrove sediment (Woodroffe, 1981; Ellison, 1993; Ellison, 2005). Using the calibrated years derived from the radiocarbon dates, sedimentation rates were calculated. The radiocarbon dates shown relative to elevation of the three cores (Figure 5) show increasing age with depth between all three cores, except for the 93-98 cm date from LW1 which is much younger relative to the other two cores. This may be indicative of disturbance within the mangrove peat, perhaps bioturbation by crabs which were found at the site. The sedimentation rate at 93-98 cm of the seaward core at Lomawai was particularly high also, at between 2.8-19.4  $\text{mm a}^{-1}$  while the sedimentation rates at the other three cores were between 1.1-2.0  $\text{mm a}^{-1}$ .

Core Site	Depth (cm)	Measured Age yrs BP	Conventional Age yrs BP	$^{13}\text{C}/^{12}\text{C}$ ‰	2 Sigma Calibration	Sedimentation Rate ( $\text{mm a}^{-1}$ )
LW1	93-98	150 +/- 40	120 +/- 40	26.8	Cal AD 1670 - 1780 (Cal BP 280 - 160)	2.8-4.2
					Cal AD 1790 - 1960 (Cal BP 160 - 0)	4.3-19.4
LW1	193-198	1110 +/- 40	1070 +/- 40	27.3	Cal AD 890 - 1030 (Cal BP 1060 - 920)	1.7-2.0
LW2	93-96	540 +/- 40	510 +/- 40	27.0	Cal AD 1330 - 1340 (Cal BP 620 - 610),	1.4
					Cal AD 1400 - 1450 (Cal BP 560 - 500)	1.2-1.7
LW3	63-71	440 +/- 40	430 +/- 40	25.7	Cal AD 1420 - 1500 (Cal BP 530 - 440),	1.1-1.3
					Cal AD 1600 - 1610 (Cal BP 350 - 340)	1.6-1.7
KB2	135	820 +/- 40	780 +/- 40	27.5	Cal AD 1200 - 1280 (Cal BP 750 - 670)	1.7-1.9

Table 3. Radiocarbon Dating Results and calculated sedimentation rates from Lomawai and Kubulau, Fiji

### 3.4 Pollen Analysis Results

The pollen diagrams show the relative representation of each mangrove taxon recorded in samples down each core as a percentage of the total pollen sum which includes mangrove taxa, non-mangrove trees, shrubs, herbs, aquatics and ferns. Other palynomorphs such as fungal spores, microforaminifera, dinoflagellates and chlorophyllaceae were excluded.

#### 3.4.1 Lomawai Core LW1

Mangrove pollen was dominant at 60-95% of the total sum throughout the seaward 3 m core with a combination of *Rhizophora*, *Bruguiera gymnorhiza*, *Excoecaria agallocha*, *Lumnitzera littorea* and *Avicennia marina* found (Figure 15). *Rhizophora* dominated for the top 95 cm at between about 60-85% with a sharp transition at 95-100 cm to domination by *Bruguiera* pollen at 60%, which fluctuates but tends to increase in domination with depth to 300 cm. Pollen concentrations through the core were between 20,000 to 55,000 grains/cm<sup>3</sup> with a few outliers at around 80,000 grains/cm<sup>3</sup> (Figure 16). The inconsistency in pollen concentrations at the top of this core may indicate some form of disturbance, which correlates with the relatively recent radiocarbon date, perhaps bioturbation by crabs which were found in the area whilst coring. There was a general decrease in percentage organics with depth from around 30% to 8% with one outlier of 50% organics found at 30 cm depth (Figure 17).

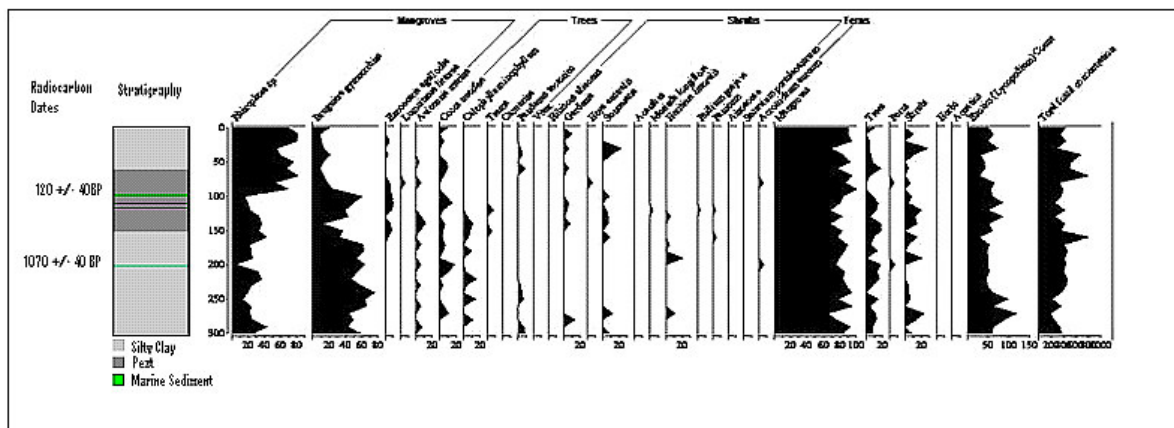


Figure 15. Stratigraphy and Pollen Diagram from Core LW1, Lomawai, Fiji (percentage based on pollen sum)

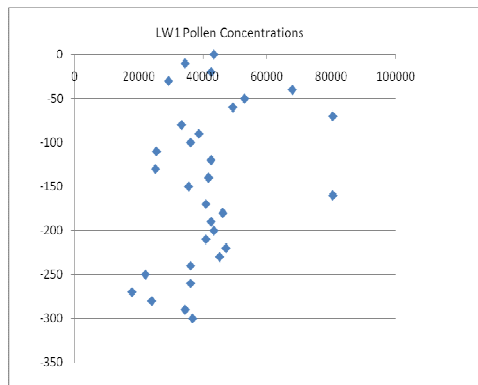


Figure 16. Pollen Concentrations from Core LW1, Lomawai, Fiji

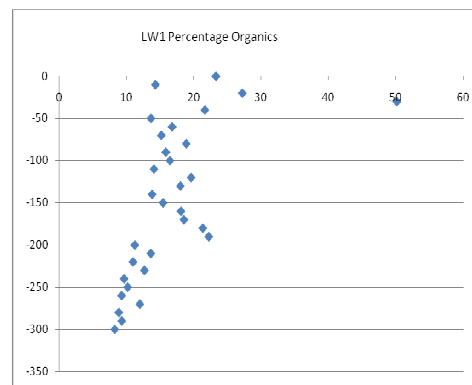


Figure 17. Percentage Organics from Core LW1, Lomawai, Fiji

### 3.4.2 Lomawai Core LW2

Pollen results show that *Bruguiera* dominated at 60% of the pollen sum at the surface, and continues to dominate between 30-60% until about 240 cm down the core, where it began to decline and *Rhizophora* became more dominant, fluctuating between 30-50% (Figure 18). Mangrove pollen was found to be 60-90% of the total sum, dropping down to 40% at the very base of the core with an increase in tree and shrub pollen. Pollen concentrations were generally between 30,000 to 60,000 grains/cm<sup>3</sup> with one outlier at 135,000 at 130 cm down the core (Figure 19). Percentage organics decreased with depth ranging from about 20% near the top to 9% lower down the core (Figure 20).

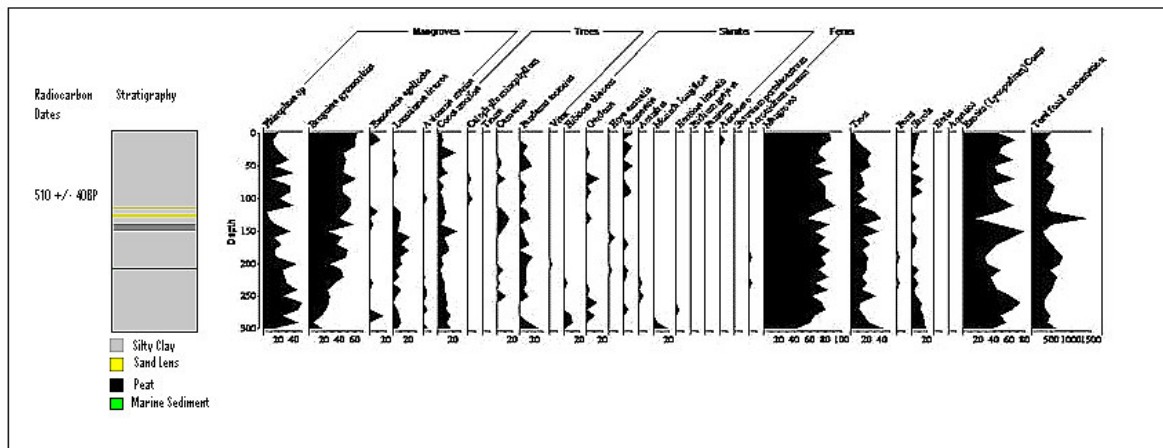


Figure 18. Stratigraphy and Pollen Diagram from Core LW2, Lomawai, Fiji (percentage based on pollen sum)

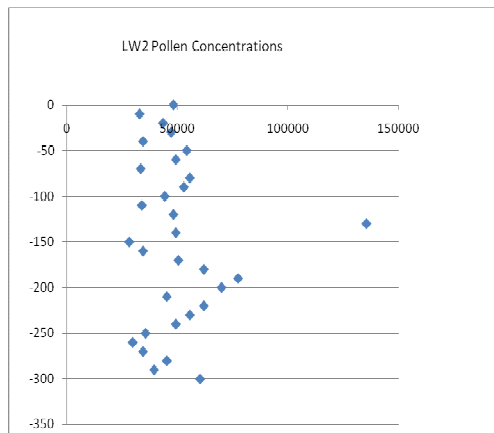


Figure 19. Pollen Concentrations from Core LW2, Lomawai, Fiji

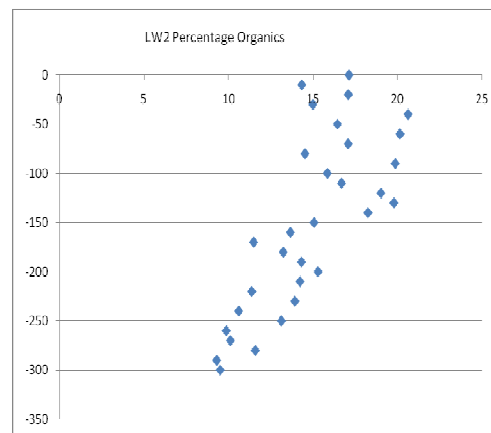


Figure 20. Percentage Organics from Core LW2, Lomawai, Fiji

### 3.4.3 Lomawai Core LW3

*Rhizophora* dominated at the top of the core before a *Bruguiera* peak between 70 cm and 110 cm (Figure 21). There was another *Rhizophora* peak between 110 cm and 130 cm before dropping off also. There was an increase in *Lumnitzera* and *Avicennia* towards the base of the core with high levels of *Cocos nucifera* found also. Mangrove pollen was around 60-100% of the total sum for the top 140 cm before dropping back to around 20% at 230 cm with a peak in tree species at concentrations up to 90% of the total sum. Pollen concentrations were between 45,000 to 12,000 grains/cm<sup>3</sup>, generally decreasing with depth, and with a couple of outlying higher concentrations found at 40 cm and 130 cm depth (Figure 22). Percentage organics were found to be much lower than in more seaward LW1 and LW2 cores, ranging from 3-15%, and did not have the decreasing trend with depth found in the other two cores in Lomawai Reserve (Figure 23).

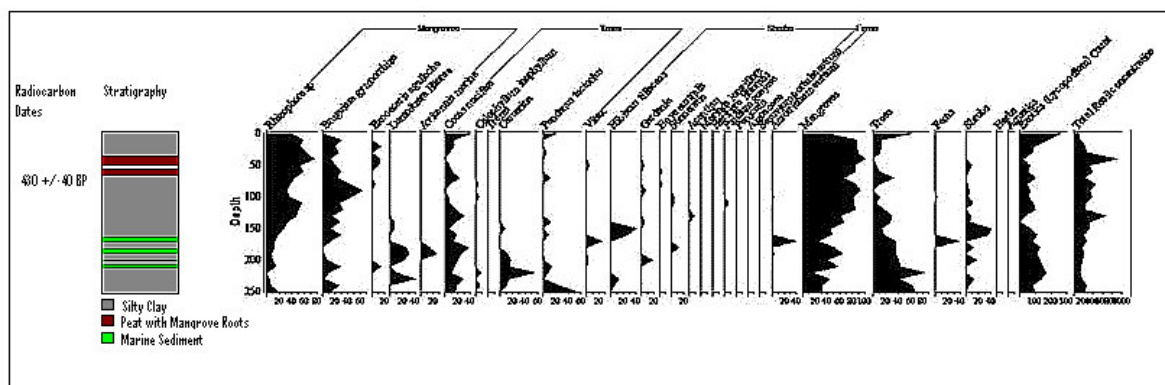


Figure 21. Stratigraphy and Pollen Diagram from Core LW3, Lomawai, Fiji (percentage based on pollen sum)

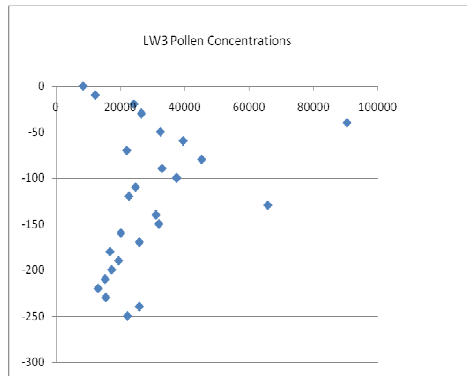


Figure 22. Pollen Concentrations from Core 3, Lomawai, Fiji

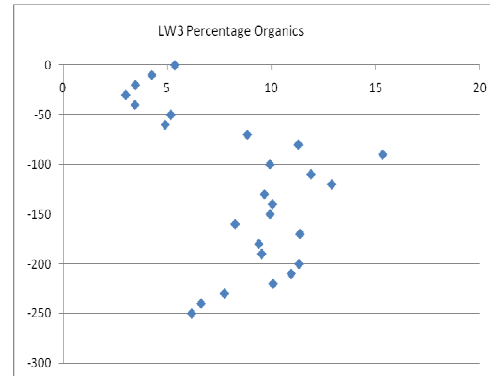


Figure 23. Percentage Organics from Core 3, Lomawai, Fiji

### 3.4.4 Kubulau Core KB1

In core KB1 mangrove pollen is consistently high throughout the core at 70-90% of the total sum (Figure 24). *Rhizophora*, *Bruguiera gynorrhiza* and *Excoecaria agallocha* each occur at about 20% until 30 cm depth, below which *Rhizophora* percentages increase to 60-75%. Mangrove Pollen concentrations range between 20,000 and 80,000 grains/cm<sup>3</sup> with no obvious trends (Figure 25). Percentage organics show a general decrease with depth from 50-17% (Figure 26).

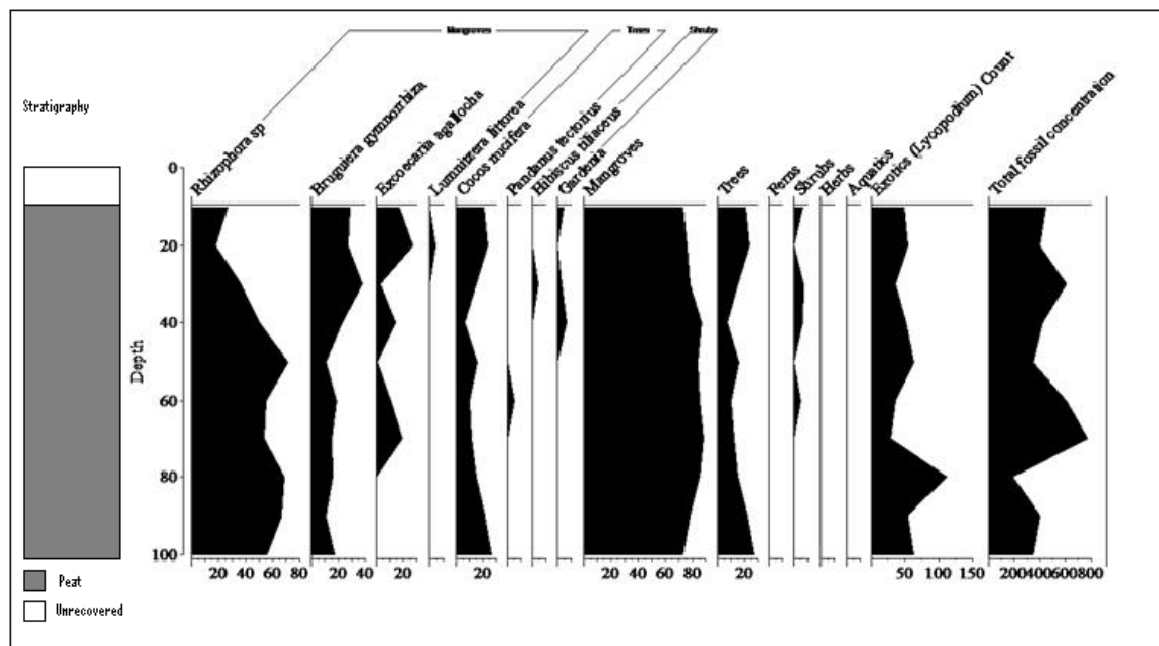


Figure 24. Stratigraphy and Pollen Diagram from Core KB1, Kubulau, Fiji (percentage based on total pollen sum)

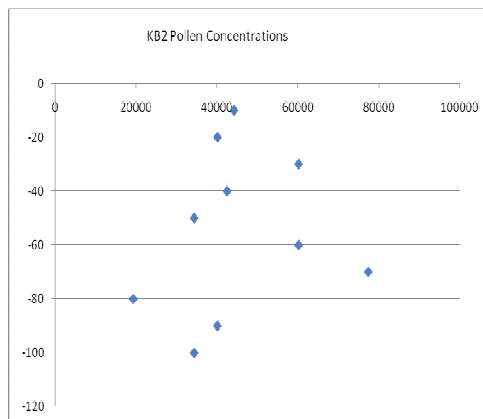


Figure 25. Pollen Concentrations from Core KB1, Kubulau, Fiji

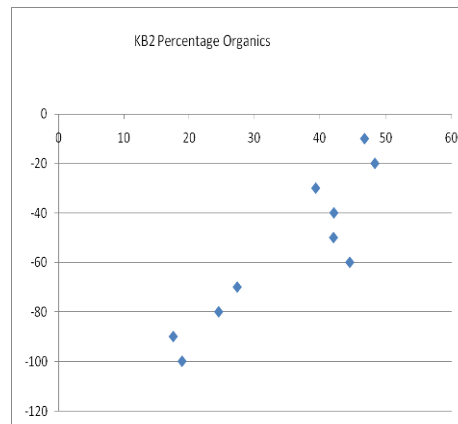


Figure 26. Percentage Organics from Core KB1, Kubulau, Fiji

### 3.4.5 Kubulau Core KB2

In core KB 2 the pollen diagram (Figure 27) shows mangrove dominance at 70-95% of the pollen sum to 130 cm depth, where there is a slight decline. *Bruguiera* and *Rhizophora* both share dominance at about 40% each with some alternation. *Rhizophora* is at its highest proportion at the base of the core at 120-130 cm depth. *Excoecaria agallocha* was also present throughout the core, as was *Cocos nucifera*. Pollen concentrations are ranging between 20,000 and 65,000 grains/cm³ with a general increase with depth (Figure 28). Percentage organics range from 45-15% throughout the core with a strong decrease with depth. The lack of record at 10 cm depth is due to unrecovered sediment from the core (Figure 29).

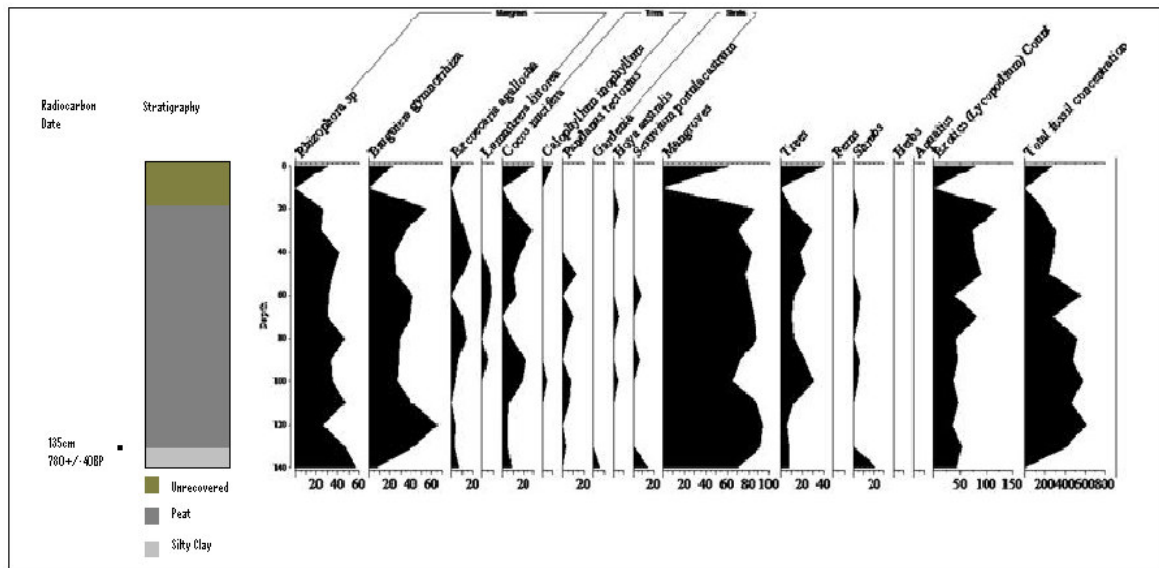


Figure 27. Stratigraphy and Pollen Diagram from Core KB2, Kubulau, Fiji (percentage based on total pollen sum).

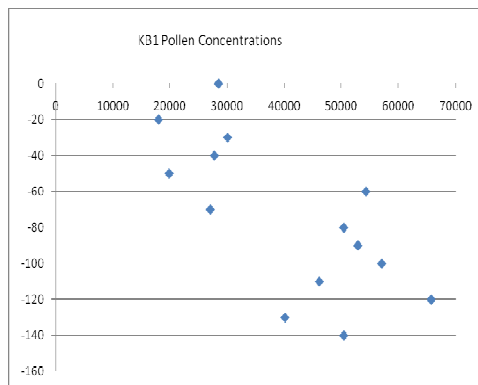


Figure 15. Pollen Concentrations from Core KB2, Kubulau, Fiji

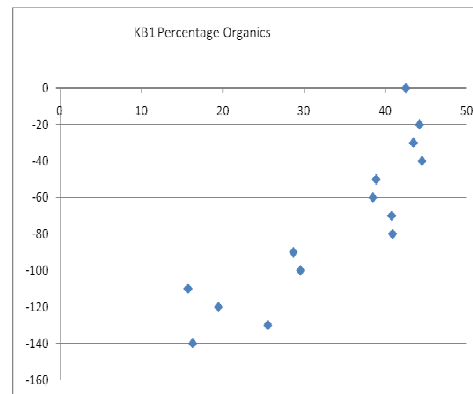


Figure 16. Percentage Organics from Core KB2, Kubulau, Fiji

## 4.0 Discussion

### 4.1 Lomawai

Elevation results demonstrated that the seaward *Rhizophora* forest extends to the seaward edge of mangroves at 2.6 m below datum, and changes to *Bruguiera* dominant forests at 1.9 m below datum, while the landward edge of mangroves with salt flat is at 1.6 metres below elevation datum (Table 2), a range of about 1.0 m. *Rhizophora* occurs across this whole range from *R. stylosa* at the seaward edge, *R. samoensis* inside this, and stunted *R. samoensis* and *R. selala* at higher elevations, while *Bruguiera* is limited to a narrow range above 1.9 m below datum. *Rhizophora stylosa* occurred from the seaward edge to the LW2 core site, an elevational difference of 0.6 m, showing that this species is broader in its elevation tolerance, which would make it more resilient to sea-level change.

Pollen diagrams from all three Lomawai cores indicate the presence of mangroves throughout the Late Holocene with the percentage of mangrove pollen consistently well above 50%. In core LW1 this extends to 300 cm depth (Figure 15), in core LW2 to 260 cm depth (Figure 18), and in core LW3 to 150 cm depth (Figure 21). These depths are 3.5 – 4.0 m below elevation datum (Figure 12). The high percentage of mangrove pollen indicates that the core sites were within a mangrove forest throughout this deposition period (Muller, 1959; Cohen and Spackman, 1977; Bartlett and Barghoorn, 1973). Hence mangroves in the past were able to occur at deeper elevations than at present, which means that the site has experienced relative sea-level rise more than the last 1,000 years as indicated by the lowest radiocarbon date in core LW1.

This seaward edge core (LW1) has the most distinctive transition with a landward community of *Bruguiera* dominating the lower part of the core with 40-60% of the pollen sum. At 100 cm from the top of the core, at around 120 years BP, *Bruguiera* suddenly declines, being replaced by a seaward community of *Rhizophora* with around 60% of the pollen sum, indicating sea-level rise and the landward migration of the mangrove swamp. The second core (LW2) which was taken in the middle of currently dense *Bruguiera* forest, has a more gradual transition from *Rhizophora* to

*Bruguiera* dominated forest over the core period. This may indicate a transition from stunted *Rhizophora*, which currently has a narrow fringe between the salt pan and *Bruguiera*, to a *Bruguiera* dominated forest as the mangrove swamp migrated landwards. The landward core on the edge of the salt pan (LW3) has a distinct transition from a tree dominant community in the lower half of the core to a mangrove dominated one in the upper half, again indicative of landward migration of the mangrove swamp.

These results of mangrove presence at depth indicate that sedimentary accretion has been mostly able to keep up with the rate of sea-level rise during the last 1,000 years. This indication of relative sea-level rise and landward migration of the mangrove swamp correlates with the occurrence of tectonic subsidence found in the area (Nunn and Peltier, 2001) and shows a similar response to mangrove communities in Southern Indonesia which have experienced relative sea-level rise as a result of tectonic subsidence (Ellison, 2005). This contrasts with results from Northern Australia which have shown fluvial sedimentary deposition to cause seaward relocation of mangroves since sea-level stabilized about 6000 years ago (Woodroffe *et al.*, 1987).

## 4.2 Kubulau

The pollen diagrams from Kubulau show mangrove pollen domination to 100 cm depth in core KB1 (Figure 24) and 140 cm depth in core KB2 (Figure 27), however it is declining at the base of core KB2. Lack of stratigraphy at this site was caused by its basalt lava confinement (Figure 7), and the mangrove area being small compared with Lomawai. The sudden fall in *Rhizophora* and peak in *Bruguiera* found at about 130 cm depth and 780 BP correlates with the drop in sea-level throughout the Pacific Basin which occurred at around 700 years BP (Nunn, 2007). This would result in the seaward progradation of mangroves and the replacement of *Rhizophora* by *Bruguiera*. The rise in sea-level which followed resulted in the reverse occurring with a rapid decline in *Bruguiera* percentages and increase in *Rhizophora*. The seaward core (KB2) shows a more gradual change from *Rhizophora* dominant forest at the base of the core before a gradual decline at about 50 cm depth to the top of the core and an increase in *Bruguiera*. The ability of this mangrove swamp to migrate inland with rising sea-levels is limited due to the steep slope of the adjacent land and presence of a large lava flow to the east of the river.

## 4.3 Sedimentation

Estuarine sedimentation rates can be calculated using the calibrated years derived from the radiocarbon dates (Table 2). Sedimentation rates between 1.1-2.0 mm a<sup>-1</sup> were found at all depths from which radiocarbon dates were obtained, except for the top of the seaward edge core at Lomawai at which the sedimentation rate increased to 4.5-11.9 mm a<sup>-1</sup>. These rates of sedimentation are all slightly higher than those found in southern Irian Jaya, which were between 2.8-19.4 mm a<sup>-1</sup> (Ellison, 2005), and in the Purari Estuary, southern Papua New Guinea, which were between 0.7-1.5 mm a<sup>-1</sup> (Thom and Wright, 1983). This is a surprising result, as the catchments in Fiji are smaller. The high sedimentation rates found at both Kubulau and Tikina Wai



show a rapidly accreting mangrove swamp which has been able to keep up with longterm relative rise in sea level. This contrasts with results from the low island Bermuda which showed the rate of sea-level rise to be exceeding the rate of sedimentary accumulation, resulting in the retreat of the seaward margin and erosion (Ellison 1993; Ellison, 2009a).

In situ mangrove sediment at this autochthonous Bermuda mangrove swamp was around 70% organic and had lower sedimentation rates of below  $1.0 \text{ mm a}^{-1}$  (Ellison, 2009a). More rapid rates at Fiji sites demonstrate allochthonous sedimentary sources with sediment coming down the rivers allowing accretion beneath the mangroves. The percent organic results were between 5-20% in Lomawai and 10-50% in Kubulau. This is relatively low compared with percent organic results of 70-76% which were found in island mangroves of the Caribbean and Bermuda Ellison, 1993; McKee et al., 2007). This study along the coasts of Belize, Honduras and Panama measured the relative rates of accumulation of root matter and their potential contribution to peat formation, concluding that subsurface accumulation of mangrove roots and other organic inputs were enabling mangroves in the region to adjust to changing sea-levels (McKee et al., 2007). However, while these mangrove islands were formed through autochthonous peat accumulation, lacking any terrigenous sediment input, the mangrove communities of Lomawai and Kubulau have significant river sediment input and a higher composition of silicates, resulting in a lower percentage of organic material from *in situ* peat formation. This indicates the importance of river systems in allowing the high sedimentation rates of both Lomawai and Kubulau, with material deposited by their rivers enabling the mangrove swamps to accumulate material at rates equaling those of relative sea-level rise in the region. This high sedimentation rate has allowed the mangroves to adapt to relative sea-level rise.

#### 4.4 Relative sea-level

Hence Lomawai has experienced relative sea-level rise, and has been keeping up with relative sea level rise rates higher than global rates in the last several hundred years, with replicated evidence of mangrove stratigraphy lower than present tidal levels. While mangroves have kept up, there has been a slow landward migration of mangrove zones over the centuries indicating that the rate or relative sea level rise has been slightly higher than the sedimentation rates of  $1.1\text{-}2.0 \text{ mm yr}^{-1}$ . At Kubulau, stratigraphy was relatively shallow, with little evidence of mangrove presence below current levels suggesting tectonic stability.

Hence both Lomawai and Kubulau mangroves are vulnerable to global increases in the rate of sea level rise, which can be mitigated by continued catchment sediment delivery.

Current projections of the IPCC 4<sup>th</sup> Assessment are for global eustatic sea level rise of  $0.18\text{-}0.59 \text{ m}$  by 2099 ( $1.5\text{-}9.7 \text{ mm a}^{-1}$ ) (IPCC, 2007). Furthermore, global mean sea level has already been rising (Bindoff et al., 2007), at an average rate of sea level rise of  $1.8\pm0.5 \text{ mm yr}^{-1}$  between 1961-2003. This study has shown that the long term net sedimentation rates in the Lomawai and Kubulau mangroves are mostly between  $1.1\text{-}2.0 \text{ mm yr}^{-1}$ , hence the top range of recent rates of sea-level rise and

the lower range of projected sea-level rise are equivalent to or in excess of mangrove sedimentation rates. Combined with regional subsidence, then the vulnerability of the mangroves increases.

## 5.0 Conclusions

This study concludes that in the last few centuries to 1,000 years ago at least, the Lomawai area has experienced relative rise in sea-level, due to regional subsidence, with the period pre-dating anthropogenic global warming. The presence of mangrove dominance pollen to depths of 3 metres at Lomawai well below seaward depth limits today, is a strong indication of relative sea-level rise in this coastal sector. The high sedimentation rates of mostly inorganic material found in this study are indicative of conditions of estuarine sedimentary accretion and progradation. However the pollen records particularly from Lomawai show the reverse has happened, with landward *Bruguiera* forest that dominates at 1-2 m depth in all cores being replaced by seaward *Rhizophora*. Together with the sedimentation results (Table 2), this indicates that relative sea-level rise has occurred throughout the Late Holocene at a rate at least equivalent to the rates of sediment accretion, resulting in continued presence of the mangrove swamp along with slow landward migration of zones. High rates of sedimentation have enabled mangroves to adjust to rising relative sea-levels and counter-act the processes of peat decomposition and physical compaction.

Rising sea-levels and the changes in climate on the predicted scales are expected to alter the position, area, structure, species composition and health of mangrove communities. This study has shown the mangroves of Lomawai to be resilient, maintaining position during sea-level rise of the last 1,000 years at least. There has been slow landward migration which demonstrates that they will be further impacted by an increase in the rate of relative sea-level rise. Vulnerability of mangroves and response to sea-level rise will also be influenced by anthropogenic disturbances and such stresses, which reduce the resilience of mangroves to adapt to sea-level rise. Growing populations in the Pacific Island region are going to increase the resource and pollutant impacts on mangrove communities in the future. The impact of these disturbances on mangroves and their resilience or ability to re-establish is dependent on the intensity, persistence and periodicity of forest disturbance and type. Impacts may include changes in species composition, sediment accretion, and biogeochemical cycles within mangrove communities, resulting in mortality for some species and changing the physico-chemical conditions for regeneration.

Monitoring programs in existence which have established mangrove baselines should be able to indicate changes in mangrove health and extent in the mangrove areas if they are maintained by the communities there. Informed coastal planning, regeneration of degraded mangrove forests, and education of communities directly adjacent to mangrove communities will increase the ability of mangroves to adjust to rising sea-levels while long-term regional monitoring is taking place.

Future global projections of rising sea-level will add to the background rates of relative sea-level rise, but indications from the palaeo record is that if sedimentation rates are maintained at current levels then the mangrove swamps at Lomawai and

Kubulau will remain resilient if sea-levels remain at the lower to mid end of the projected rates.

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